The impact of a premium based tick size on equity option liquidity

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Abstract: On June 2, 2009, NYSE LIFFE Amsterdam reduced the tick size for options trading at prices below €0.20 from €0.05 to €0.01 and on April 1, 2010, the exchange increased the price threshold to €0.50. We study the effect of that tick size reduction on the liquidity of individual equity options. In this respect, this study is uniquely positioned in the options context where moneyness is a clear additional factor in the implementation of the tick size changes. We show that, in general, quoted and traded option liquidity increased but at a rate decreasing with option moneyness. Real costs have fallen more for the lower priced contracts. Importantly, we show that the ability of the market to absorb larger trades has diminished after the change in the tick size. We document a substantial increase in quote revisions that implies a deterioration in the order book, as it allows traders to take advantage of the price priority rule and step ahead of larger trades. Finally, the decrease in the tick size has led to increased speculative trading behaviour.

Keywords: Liquidity, Tick Size, PBTS, Equity options, Amsterdam LIFFE

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1. INTRODUCTION

On June 2, 2009, NYSE LIFFE introduced the Premium Based Tick Size rule (henceforth PBTS) on all single stock options trading at NYSE LIFFE Amsterdam. According to the new rule, equity options trading at a premium of €0.20 or lower could be quoted at a tick size of €0.01, whereas options trading at prices higher than the threshold continued to be quoted at a minimum tick of €0.05. On April 1, 2010, NYSE LIFFE increased the price threshold from €0.20 to €0.50. This paper presents evidence on the effect of the implementation of the PBTS on the quote and trade liquidity of individual equity options. In this respect, this study is uniquely positioned in the options context where moneyness is a clear additional factor in the implementation of the tick size changes.

Theoretically, Harris (1994) suggests that a decrease in tick size is expected to lead to a narrowing of spreads if the current tick size is greater than the size that would be quoted if no minimum tick was enforced. Most importantly, spreads are expected to narrow more for the lower priced assets for which the minimum tick size is a more binding constraint. Also, to the extent that there is a negative association between trading volume and spreads, the reduction in tick size would increase trading volume. Meanwhile, market depth is expected to decrease. This is because traders desiring trade large sizes may be deterred since the small tick size increases the probability that other smaller traders may step ahead of them in the order book. On this latter point, Portniaguina et al. (2006) show that in hybrid markets like the NYSE, a reduction in tick size reduces the value of a limit order which may lead to the order book becoming very thin and quoted spreads becoming very wide as a consequence. The authors show that a decrease in the minimum tick size increases the cost of submitting large orders and subsequently leads to order splitting (stealth trading). However, the effect of this change on specialist participation rates is not expected to be uniform. For stocks with a smaller initial average trade size, order splitting should not be as prevalent as for firms with large initial trade sizes. Portniaguina et al. (2006) show that market maker profits will be positive for the former stocks and less positive, or possibly negative, for the latter.

Empirically, in equity and futures markets, several studies have shown that a reduction in tick size delivers two main outcomes. First, spreads generally narrow (see Harris, 1991, 1994; Seppi, 1997; Bollen et al., 1998; Goldstein and Kavajecz, 2000; Jones and Lipson, 2001; Bessembinder, 2003; Smith et al., 2005). Second, market depth deteriorates as a smaller tick size makes front running more profitable for smaller investors and increases order transparency for large traders (see Harris, 1996; Angel, 1997; Goldstein and Kavajecz, 2000; Jones and Lipson, 2001). The latter implies an overall increase in liquidity for small trades and an overall decrease for institutional trades. Also, Bourghellea and Declerck (2004) show that a tick size change is not necessarily associated with a change in liquidity supply but primarily affects order submission strategies. This is due to the fact that a decrease in the tick size fails to attract liquidity providers on the limit order book and, if the spread remains unaffected, depth generally still reduces.

From the empirical perspective, the issue is far from being resolved in favour of smaller tick sizes. In 2001, NASDAQ and NYSE replaced the fractional price system with decimal prices, cutting the tick size to one cent for both markets. However, in June 2013, the U.S. Securities and Exchange Commission has been reported to draft a pilot program that would increase the tick size for 100 of the smaller or less liquid US stocks (see Mamudi and Michaels, 2013). This has been in response to criticisms from the financial industry that "decimalization — a euphemism for the collapse in trading spreads, tick sizes and commissions — decimated the U.S. IPO market" (Weild et al., 2012, p. 2). In their view, it is crucial to provide economic incentives to market makers in order to continue supporting small stocks and provide analyst coverage. In this respect, our study is extremely timely. Also, for NYSE LIFFE, market makers are an integral part of the trading process as, under their contractual obligations with the exchange, they are obliged to offer competitive two-way quotes across the whole spectrum of contracts that are trading at the exchange. In this respect, the implementation of the PBTS may lead to lower profits for market makers which may serve as a disincentive to offer competitive quotes. On the other hand, Harris (1994) suggests that since market maker profits are a function of volume and spreads, their profits would overall increase if volume increases by more than the decrease in spreads. However, Al-Yahyaee (2013) shows that a decrease in tick size does not always lead to increases in trading volume.

Liquidity has multiple dimensions, namely spread, depth and execution speed. Spread refers to the round-trip cost of trading, depth measures the supply of liquidity and execution speed refers to how quickly orders are filled. As we don't have information on how long limit orders remain in the order book, we capture the latter dimension by measuring quote revisions, that is the percentage of quote updates at a given interval. The assumption is that an increase in quote revisions implies greater costs for market participants. We also provide evidence on two hybrid measures of liquidity that combine spread and depth, namely quoted slope (see Hasbrouck and Seppi, 2001), which we refer to as quote liquidity, and effective spread, which we refer to as trade liquidity.[1]

Our findings suggest that while spread liquidity generally increased more for the deep-out-of-the-money options, depth liquidity deteriorated more for contracts that are further in-the-money. This implies that, following the tick size changes, quoted liquidity generally increased for the deep-out-of-the-money (DOTM) and the out-of-the-money (OTM) contracts, but at a decreasing rate for greater moneyness. Similarly, effective spreads decreased more than quoted spread for contracts with low moneyness but the significance

[1] Section 4 discusses why we use effective spreads and quote slope as hybrid measures of trade and quote liquidity respectively.

disappears as moneyness increases. For calls priced under €0.20, this drop in effective spreads is due to an overall decrease in real costs net of the price impact of trades. For contracts priced between €0.20 and €0.50, the decrease in spreads is due to a decrease in price impact rather than a decrease in real costs.

Importantly, we show that the ability of the market to absorb larger trades has diminished after the tick size change. However, as 60% of trades are retail (see Noiville and Seblain, 2011), we expect that this decrease in liquidity has no effect for the vast majority of traders in the market. Consistent with previous findings, trading activity generally increased after the tick size changes, also implying an increase in riskier trading activities. We document an increase in the volatility for the DOTM puts that is consistent with the hypothesized increase in the speculative behaviour for these contracts. Finally, we document a substantial increase in quote revisions. This finding shows strong support for the hypothesis that the decrease in tick size has potentially led to deterioration of the order book, as it allows traders to take advantage of the price priority rule and step ahead of larger trades.

Our findings have important implications for optimal contract design in the equity options market. The goal of attracting liquidity has been achieved with two immediate implications: economic rents have been transferred from market makers to individual investors and the increase in liquidity has been realized at the expense of a thinner market for larger investors. The price/time priority rule may not work in circumstances when a large trade enters the market and, in such occasions, market makers should be allowed to increase their economic rents for facilitating abnormal trade sizes in ways similar to an upstairs market. A second possible scenario would be for the exchange to introduce a pro-rata algorithm that will circumvent the problem with the price priority rule when the tick size is too small.

The rest of the paper is organized as follows. Section 2 discusses the market structure. Section 3 discusses the positioning of the paper and outlines the testable hypotheses. Section 4 describes the data and research design issues, Section 5 presents the analysis and Section 6 concludes.

2. NYSE LIFFE AMSTERDAM MARKET STRUCTURE

NYSE LIFFE is the derivatives branch of NYSE for the European derivatives market, overseeing a total of five European markets (Amsterdam, Brussels, Lisbon, London and Paris). Trading on NYSE LIFFE takes place via LIFFE CONNECT, an anonymous, electronic order-driven system, and liquidity is supported by the "Euronext Liquidity Provider System" (ELPS). ELPS operates on the basis of market makers acting as liquidity providers with the obligation to submit continuous asks and bids in near-the-money contracts and receive trading rebates as a return.[2]

NYSE LIFFE implemented the new tick size for all options trading below €0.20 with effective date June 2, 2009. The exchange stated that the "PBTS is designed to have the tick size match the level of the premium: a small tick size for lower prices and a large tick size for higher prices". Further, the exchange added that since the introduction of the new tick size, spreads have almost halved for the affected contracts (see PBTS, 2013).

The implementation of the PBTS rule on NYSE LIFFE Amsterdam is unique from several perspectives. First, trading at NYSE LIFFE is facilitated by a liquidity provider scheme, the "Euronext Liquidity Provider System" (ELPS). For Amsterdam, the exchange recognizes three types of liquidity providers, the Primary Market Makers (PMMs), the Competitive

[2] "How the Euronext.liffe markets work". Available on the NYSE LIFFE website.

Market Makers (CMMs) and the Extra Competitive Market Makers (CMXs). Market makers' spread and size obligations are a function of the price and volatility of the underlying asset (updated semi-annually) and refer to maximum spread and minimum size (e.g. a maximum spread of 50p and a minimum size of 10 contracts). Spread and size obligations are therefore not uniform across all assets. All market makers are required to trade a minimum number of contracts of high liquidity assets.[3] Trading fee reductions are not uniform and are based on a monthly evaluation of the market maker's performance. Second, an important feature of the ELPS in Amsterdam is that PMMs are obliged to offer two-way competitive quotes for the entire series of contacts for which they are contractually obligated to offer liquidity. This implies that PMMS are obliged to offer continuous quotes for at least 85% of the relevant number of series and during at least 85% of the specific time period. However, CMMs and CMXs are obliged to offer liquidity for the near-the-money contracts only. The above imply that the implementation of the PBTS affects PMMs' quote obligations more than CMMs or CMXs, as the PBTS is mostly relevant for the OTM options that are priced at lower levels than the remaining options. With respect to market makers' willingness to offer competitive quotes at a smaller tick size, Harris (1994) shows that when tick size decreases, market makers may have a smaller incentive to submit quotes that are binding when it is relatively cheap to obtain price priority at a market with a smaller tick size. Third, NYSE LIFFE Amsterdam is heavily dominated by retail investors (see Noiville and Seblain, 2011) and concerns have been raised regarding the potential impact of PBTS on boosting the trading activity for the OTM options, arguing that trading OTM options will remain too costly as brokerage retail fees are high, taking away any savings from trading at a smaller fee (Fooling retail investors with new tick size, 2009).

[3] Asset liquidity and hence the number of market makers for each asset is assessed and defined by the exchange.

3. HYPOTHESES

The implementation of the PBTS is expected to have an effect on three features of trading in equity options: liquidity, trading activity and volatility. In Section 1, we outlined the main measures of liquidity: quoted spread, depth and execution speed. In the section below, we develop the hypotheses with regard to each measure and also with regard to the anticipated effects of the PBTS on trading activity and volatility.

While the evidence from literature on the effect of tick size reductions on asset liquidity is overwhelmingly positive for the spread aspect of liquidity, deteriorations in depth may lead to an overall increase in transaction costs for larger trades. There is a large number of studies that report narrower spreads following a tick size reduction (see Harris, 1991 and 1994; Seppi, 1997; Bollen et al., 1998; Goldstein and Kavajecz, 2000; Jones and Lipson, 2001; Bessembinder, 2003; Smith et al., 2005), however Goldstein and Kavajecz (2000) and Jones and Lipson (2001) report a decrease in depth for NYSE stocks after decimalisation. Also, for the UK Long Gilt futures market, ap Gwilym et al (2005) show that while depth decreased following a move to decimal pricing, the spread, measured in ticks, increased but the monetary value of the spread decreased. With regard to effective spreads as a hybrid measure of liquidity, Bessembinder (2003) reports that effective spreads have generally declined for NYSE and NASDAQ stocks after decimalisation and that small capitalisation stocks benefitted most from the reduction in tick size. No studies exist on the quote slope as a hybrid measure of quote liquidity, nevertheless, we anticipate a reduction in quote slope if overall liquidity has increased. We thus derive the following hypotheses:

Contracts that trade under a smaller tick size will:

Hypothesis 1: *Exhibit a decrease in quoted spreads*

Hypothesis 2: *Exhibit a decrease in depth*

Hypothesis 3: *Exhibit an increase in trade and quote liquidity if the benefit from a reduction in the cost side of liquidity is greater than the cost of a decrease in liquidity supply*

Effective spreads can be further decomposed to two components: the price impact, which measures losses of investors to informed traders, and the realized spread which measures the post-trade price reversal or equally the cost of providing liquidity net of losses to informed traders (see Bessembinder and Kaufman, 1997). If the smaller tick reduces spreads, both the price impact and the realized spread measures will fall as a consequence. In practice, this implies that there should be smaller price jumps in either direction with the smaller tick size. Most important, however, is the relative change of realized spreads to price impact. Realized spreads measure market making profits and, hence, a greater reduction in realized spreads as compared to price impact would imply that the hypothesized decrease in traded liquidity is more a function of a drop in real costs. We derive the following hypotheses:

Hypothesis 4: *Price impact and realized spreads will be smaller for contracts that trade under the new tick size*

Harris (1994) shows that trading volume will increase following a decrease in tick size. Also, transaction frequency may increase as it is cheaper to trade smaller sizes and reduce the cost of being a counterparty to informed traders. Bacidore (1997) reports that trading volume did not significantly increase at the Toronto Stock Exchange following the reduction of tick size. The same finding is reported for AMEX (see Ahn et al., 1996). On the other hand, following the increase of the tick size for the S&P500 futures contract trading at CME, Bollen et al. (2003) show an overall widening in spreads and a significant reduction in trading volume. Finally, Chakravarty et al. (2003) has shown that while trading volume and the number of trades increased for small NYSE stocks following decimalisation, there was a significant decrease in trading activity for large size trades. Harris (1994) also predicts that a reduction in tick size will have more visible effects on the trade liquidity of the more heavily traded stocks, because it is more likely that the previous larger tick size acted as a binding constraint for a narrowing of spreads on these stocks. We subsequently derive the following hypotheses:

Hypothesis 5: *Contracts that trade under a smaller tick size will exhibit an overall increase in trading activity*

Hypothesis 6: *Trade liquidity will increase more for assets that are more heavily traded*

An important aspect of the implementation of the PBTS is that it is expected to have an asymmetric effect on option contracts based on the moneyness of those contracts. In particular, PBTS is aligned to the option price and as a result the effect should be stronger for the OTM options, since these are the options that are the lowest priced across moneyness. PBTS is also expected to have a stronger positive effect for the OTM contracts that are more likely to expire in-the-money (ITM). The probability of exercise is negatively related to moneyness, with deeper OTM options being less likely to be exercised at maturity, i.e. to expire ITM, ceteris paribus. In addition, the probability of exercise at maturity for OTM options with the same moneyness is positively related to the underlying asset's volatility. For instance, the price of a more volatile underlying asset is more likely to exceed at maturity the high strike price of a currently OTM call, compared to an equally OTM call written on an underlying asset with lower volatility. A similar argument applies in the case of OTM puts, where the prices of more volatile underlying assets are more likely at maturity to fall below the low strike prices of currently OTM puts.

Overall, we hypothesize that as OTM options written on more volatile underlying assets have a higher probability of being ITM at expiration, the impact of the tick size change will be greater. Intuitively, we would expect traders to find these contracts more attractive for speculative activities due to their higher probability of exercise at expiration, compared to equally OTM options written on less volatile assets. Consequently, a large tick size would constitute a greater constraint on trading these contracts with higher underlying volatility, and we anticipate a greater impact on their liquidity following a reduction of the tick size. In relation to the above, previous research suggests that if decreases in tick size are associated with lower liquidity then volatility should also increase (see Harris, 1994; Bessembinder, 2003). Overall, we hypothesize the following:

Hypothesis 7: *Liquidity will increase by less as moneyness increases*

Hypothesis 8: *The reduction in Spreads for OTM options written on more volatile underlying assets after the implementation of the PBTS will be greater compared to equally OTM contracts written on less volatile assets*

Hypothesis 9: *Option spreads that are affected by the PBTS will exhibit lower volatility reflecting an overall increase in liquidity*

Finally, whilst it is not possible to measure execution speed directly, we assume that the latter is related to the percentage of quote revisions per time interval. In particular, the reduction in tick size is hypothesized to have a significant effect on quote revisions. More specifically, a smaller tick size reduces the cost of stepping ahead of other traders in the order book, and we hypothesize that quote revisions may significantly increase for those contracts that are affected by the implementation of the PBTS. Hence, we assume that an increase in quote revisions implies greater costs for market participants. Bessembinder (2003) shows that neither NYSE nor NASDAQ exhibited any systematic increase in price reversals after the decrease in tick size:

Hypothesis 10: *The number of quote revisions will increase for the contracts that are affected by the PBTS*

4. RESEARCH DESIGN

The intraday dataset contains information on maturity date, strike price, volume and price for all individual equity options (henceforth tickers), time-stamped to the nearest second, separately for asks, bids and trades. [4] Each ticker is trading under different contracts, which vary by the strike price, maturity date and contract type, i.e. call or put (henceforth sub-tickers). We select options that expire within a maximum of 365 days, but not within seven days, since we want to avoid any very short term and very long term expiration effects. Moneyness is defined as S/K, where K refers to the option strike price and S to the underlying unadjusted opening price.[5] For each contract type (call or put) we categorize sub-tickers according to their moneyness level and days to expiration. For calls, we define DOTM contracts with moneyness smaller than 0.9, OTM contracts with moneyness equal to 0.9 but smaller than 1.00 and in-the-money (ITM) contracts with moneyness between or equal to 1.00 and 1.10. We drop contracts that are deep-in-the-money (moneyness > 1.10) as very few observations fall in this category. The opposite classification is used for puts.

[4] The number of tickers reflects the total number of firm-options trading at the exchanges and includes delisted options.

[5] End-of-day prices for the underlying stocks are obtained from DataStream. We drop tickers for which we failed to identify their underlying instruments from DataStream. All options in the sample are American style. We drop the newly introduced weekly and daily options contracts. In total, 90 percent of contracts are maintained in the final sample.

We delete outliers based on spread and price criteria as follows. All zero volume, zero price and out-of-hours observations are deleted.[6] Quotes with negative or zero bid-ask spreads are dropped from this sample. Also, as in Wei and Zheng (2010), we control for possible outlying data by dropping quotes with excessively large bid-ask spreads. The cut-off point for the percentage bid-ask spreads is set at 150% for the in-the-money options and 200% for the out-of-the-money options.

We focus on a 300-day window around the implementation of the PBTS rule and its subsequent update. The sample is split into four subsamples. The first refers to the days prior to the initial implementation of the PBTS (henceforth Stage 1) at a threshold price of €0.20 (January 3, 2009 to June 1, 2009), the second to the dates after the implementation of the PBTS (June 2, 2009 to October 30, 2009). The third and fourth periods refer to the days before (November 2, 2009 to March 31, 2010) and after (April 1, 2010 to August 29, 2010) the increase of the price threshold to €0.50 (henceforth Stage 2).

The estimation of quoted spreads, depths and option returns is based on sub-ticker mid-quotes which are calculated at 5 minute intervals from bid and ask prices as follows. On each trading day, we select the first quote of the day, which is however quoted no later than 8.01am. We then retain bid and ask quotes at five minute intervals, and we control for stale pricing by dropping bid and ask prices that are recorded more than two minutes prior to each five minute interval. For the closing return (16:30pm), a two-minute rule applies. We only estimate midquotes when both ask and bid prices are found within the aforementioned intervals. For the remaining intervals no midquotes are estimated. The above procedure

[6] All three exchanges are open between 08:00 and 16:30 (London time). We delete half-days. There are no zero-volume trades in the raw dataset. However we include this restriction in any case in our sample, as the sample contains reported trades, hence all trades should contain a reported traded volume. The latter is an important distinction from datasets where market orders may contain zero volume (pre-reporting).

allows us to retain the maximum number of observations at regular time intervals, controlling at the same time for the biases of missing variables and stale pricing. In total there are 103 intraday intervals per day, however we drop the opening and closing intervals, hence *n* denotes the total number of intervals (101) and *i* denotes each five-minute interval for each day *t*.

The most commonly used spread measure is the quoted bid-ask spread, defined as the difference between the most recent ask and bid prices (see Petrella, 2006, Cao and Wei, 2010 and Wei and Zheng, 2010). For each sub-ticker, we control for the price level differences by calculating the percentage bid-ask spread ($PBAS_t$), defined as the ratio of quoted spread over the quote midpoint:

$$PBAS_{5-min} = 100 \times \frac{Ask_{5-min} - Bid_{5-min}}{M_{5-min}} \tag{1}$$

where $Ask_{5\text{-}min}$ and $Bid_{5\text{-}min}$ are the ask and bid prices sampled at 5-minute intervals, respectively, and $M_{5\text{-}min}$ is the trade midquote defined as half the sum of bid and ask prices at each interval.

A reciprocal measure of liquidity is quoted depth (see Harris, 1990). We measure quoted depth (*Depth*) in number of contracts as follows:

$$Depth_{5-min} = \frac{Volume_{ask,5-min} + Volume_{bid,5-min}}{2} \tag{2}$$

where $\mathrm{Volume}_{\mathrm{ask,5\text{-}min}}$ and $\mathrm{Volume}_{\mathrm{bid,5\text{-}min}}$ refer to the number of contracts quoted at the ask and bid prices, respectively.

A measure that combines the price information from the calculation of spreads and the quantity information from the calculation of depths is the Log Quote Slope that is defined as follows:

$$Log\ Quote\ Slope_{5-min} = \frac{\log(Ask_{5-min}/Bid_{5-min})}{\log\left(Volume_{ask,5-min}\right) + \log(Volume_{bid,5-min})} \tag{3}$$

The Log Quote Slope measures the slope of a line connecting the bid and ask price/quantity pairs (see Hasbrouck and Seppi, 2001). Hence, liquidity will improve if either the size of ask or bid increases or if the spread decreases. The Effective Half Spread is used as a second measure of hybrid liquidity as, even though it does not contain a direct measure of quoted depth, it provides an ex-post estimate of the effect of a large trade in the best bid and ask. If, for example, a large trade has consumed more than one level of the limit order book, the effective spread will be worse than the quoted spread. The realized spread is a measure of transaction costs net of price impact. The latter is a measure of adverse selection costs. Trades are sampled at irregular intervals and for the calculation of effective spreads, we select the most recent bid and ask prices which are within five seconds to two minutes prior to each trade. For the calculation of price impacts, we use the five-minute midquotes that are within a four-minute to eight-minute time frame after each trade.

We calculate effective spreads as follows (see Venkataraman, 2001):

$$EffSpread_t = 200 \times D \times \frac{Price_t - Midquote_t}{Midquote_t} \tag{4}$$

Where D is a trade indicator dummy that takes the value of -1 if the trade is classified as a sell and +1 if it is classified as a buy. We use the quote method to classify trades. For the trades that are not classified, we use the trade method. Less than one percent of trades are not identified with either method and are, hence, dropped from the sample. We calculate price impacts as follows:

$$Price\ Impact_t = 200 \times D \times \frac{Midquote_{t+1} - Midquote_t}{Midquote_t} \tag{5}$$

Finally, we calculate realized spreads as follows:

$$RealSpread_t = 200 \times D \times \frac{Price_t - Midquote_{t+1}}{Midquote_t} \tag{6}$$

Where Midquote_{t+1} refers to the midquote recorded within a four-minute to eight-minute time frame after each trade.

Logarithmic intraday returns (r) are calculated on midquote prices at a sub-ticker level. However, while dropping observations with excessively large spreads may alleviate the problem of outlying data for spreads, the problem still remains for the calculation of returns, as large jumps may still be recorded. Also, a problem arises with the calculation of realized volatility in less liquid markets, as the definition of realized volatility (sum of intraday squared returns) implies that returns are estimated for all intraday intervals. We alleviate this problem as follows. First, we drop returns whose absolute value is greater than three standard deviations from their mean per ticker. This allows us to retain 99 percent of the estimated returns. Returns are averaged for each ticker at an intraday level. Second, we use the absolute value of intraday 5-minute returns as a measure of intraday volatility. For the comparison tables, we use the standard deviation of the absolute intraday returns. For the trading activity variables, we calculate the number of transactions per day, trade volume per day and the average daily trade size.

We report results based on the non-parametric Wilcoxon rank sum test. Comparisons across periods 1 and 2, and 3 and 4 are based on contracts that are priced below €0.20 and €0.50, respectively. This allows us to keep the price level constant. The procedure is as follows. First, we classify all contracts to baskets according to their contract type (call/put) and moneyness (DOTM, OTM, ITM). All variables are calculated per asset and sub-period. We then perform the t-test and Wilcoxon rank sum test on the differences in the cross-sectional variation in the ticker-specific variables for the differences between sub-periods one and two, and separately for sub-periods three and four. The reported estimates are based on equally-weighted averages across tickers for each sub-period.

We decide to estimate the effect of tick size changes on liquidity by employing a difference-in-difference (DiD) model that will allow us to control for the contemporaneous effects with a set of contracts that are trading at the same time when the changes took place.[7] The DiD model is summarized below.

$$Liq_{it} = \alpha + \beta Treatment_t + \gamma Post_t + \delta Treat_t \cdot Post_t + \varepsilon V_{it} + z_{it} \tag{7}$$

[7] In a similar context, Marsh and Payne (2012) use a DiD approach to investigate the effect of short sale restrictions on market quality indicators

- Liq is the liquidity variable of interest (quoted spread, effective spread, depth, price impact, realized spread)
- Treatment is a dummy variable that takes the value of 1 for options that are affected by the implementation of the PBTS. This implies that in the first set of regressions (for calls and puts and in moneyness levels), Treatment equals 1 for options priced equal to or below 0.20. In the second set of regressions, we use options priced between 0.20 and 0.50.
- Post is a dummy variable that takes the value of 1 for the dates after the implementation of the PBTS. For the first set of regressions, Post takes the value of 1 for all dates from 2 June 2009 until 30 October 2010 (Subsample 2). The base period for the first set of regressions is January 3, 2009 to June 1, 2009 (Subsample 1). In the second set of regressions, Post takes the value of 1 for all dates from April 1, 2010 until August 29, 2010 (Subsample 4). The base period refers to dates from November 2, 2009 to March 31, 2010 (Subsample 3).
- V is a vector of control variables for the options and the underlying market. The variables of interest are 1/Price (Pr), return volatility (Vol) and the natural logarithm of trading volume (TrV) for the options market. Volume is excluded when depth is the dependent variable. We anticipate that liquidity will be positively related to the reciprocal of price and to volatility and negatively related to volume (see Chung et al., 2004, Harris, 1994). For the underlying market, we include the natural logarithm of the market capitalization of the underlying asset (MV), underlying volatility (Vol) and the closing percentage bid-ask spread (PBAS). We use the range estimator as a measure of the underlying market volatility (see Petrella, 2006). We expect higher liquidity for the larger assets. Also, we expect liquidity to deteriorate with increasing

levels of PBAS and with decreasing levels of underlying volatility (see Wei and Zheng, 2010).

The DiD allows us to extract the following information:

- α picks up the level of liquidity of options that are not affected by the PBTS rule before the implementation of the PBTS rule
- β picks up the level of liquidity of options that are affected by the PBTS rule before the implementation of the PBTS rule
- γ picks up the change in the liquidity of options that are not affected by the PBTS rule after the implementation of the PBTS rule
- δ picks up the change in the liquidity of options priced below the price threshold after the implementation of the PBTS rule

In order to estimate Equation (7), the control group includes all options that are priced under €1.00 but greater than €0.50. This allows us to maintain the price level relatively constant. We estimate Equation (7) separately for calls and puts and also for each moneyness level. All regressions are reported with double-clustered robust standard errors that allow for dependence across time and also across stocks (see Marsh and Payne, 2012).

5. ANALYSIS

Table 1 presents the effect of the implementation of the PBTS on the liquidity measures, separately for calls and puts and also across moneyness levels. In line with Hypothesis 1, in the first stage of the PBTS, quoted spreads for contracts priced under €0.20 declined significantly. The average quoted spread for the DOTM call contracts pre-PBTS was 61.6% and the average quoted spread post-PBTS is 40.6%, a drop of 34%. Also, spreads for OTM calls dropped by 49% and those for ITM dropped by 55%. The drop in quoted spread is significant for all moneyness levels and for both calls and puts. In the second stage of the PBTS, the drop in spreads is also significant for the DOTM, OTM and ITM contracts, nevertheless the magnitude of the change is smaller as the price level effect is stronger.

insert Table 1 around here

Quoted depth has also dropped substantially across moneyness levels and for both puts and calls, a finding that confirms Hypothesis 2. During the first stage of PBTS, quoted spreads fell by 58% (61%) for DOTM calls (puts), 67% for OTM contracts and 64% (71%) for ITM calls (puts). On average, the increase in quoted spread liquidity is followed by a larger decrease in quoted depth liquidity. For the larger price threshold, the drop in depths is also highly significant across all moneyness levels. An important finding is that while before the implementation of PBTS, there were large differences in the number of quoted contracts across moneyness levels, after the introduction of the PBTS the number of contracts remains relatively constant across moneyness (378 contracts to 413 for contracts priced below €0.20 and 293 to 426 for contracts priced between €0.21 and €0.50).

Consistent with Hypothesis 3, quote and trade liquidity have increased substantially during both stages of the implementation of the PBTS. The reduction in Log Quote Slope ranges from 21.42% (13.20%) for DOTM calls (puts) to 42.85% (43.58%) for ITM calls (puts). A similar, albeit less pronounced, drop is documented for the 2nd stage of PBTS. Effective spreads for the DOTM calls almost halved from 42.08% to 21.73%. For the OTM and ITM calls, the increase in traded liquidity is approximately 58%. For puts, the equivalent drop in effective spreads is 43.26% for the DOTM, 56.61% for the OTM and 57.96% for the ITM puts. The above findings imply that, while quoted liquidity increased since the 1st stage of the PBTS, effective spreads have decreased at an even greater percentage. A significant drop in effective spreads is also documented for the 2nd stage of PBTS.

insert Figure 1 around here

Figure 1 demonstrates the evolution of quoted depth and spread in the days prior to and after the implementation of the PBTS rule. We report the cross-sectional average of contracts trading 50 days before the tick size change for calls only. Clearly, quoted spreads dropped significantly at the introduction of the new tick size, however during the first stage of the PBTS, this reduction in spreads is gradual and the new stable level was reached after 10 calendar days. In contrast, quoted depths decreased significantly on the first day of the new tick size. As expected, during the 1st PBTS stage, the ITM contracts are more volatile as there is less trading under €0.20 at any time period. During the 2nd stage of the PBTS, the decrease in spreads is documented in the first day of the new rule, a finding that implies that the larger tick size is more binding the higher the option price.

insert Figure 2 around here

Figure 2 reports the outcomes of the same investigation for the quote and trade liquidity measures. An interesting finding is that for the 1st PBTS stage, trade liquidity is significantly reduced, however this is not the same for quote liquidity which seems to remain relatively constant. This finding implies that the drop in depth becomes larger as moneyness decreases. The same pattern is observed for the DOTM options at the 2nd stage of PBTS. Overall, Figure 2 implies that the increase in liquidity is bounded by the increase in quoted depth. We investigate this claim further below.

As market depth deteriorates, a question remains regarding the extent to which larger trades are affected by the drop in the number of contracts offered at the best bid and ask. We attempt to answer this question in Figure 3. Here, we are mostly concerned with the out-of-the-money contracts, as these are the contracts for which the order book is thinner.[8] We plot the cross-sectional quoted depth from Figure 1 against the time series of the average trade size in the days surrounding the tick size change for the thresholds of €0.20 and €0.50. In addition, we also plot two time series for the expected deviation from the average trade size per day: the first is calculated as the sum of the average trade size plus one standard deviation of that average for the particular day, and the second is the sum of the average trade size plus two standard deviations. We expect that on average 68% of trades will be within one standard deviation from the average trade size, and 95% of trades within two standard deviations from the average trade size. In the first two plots of Figure 3 we present the results for the DOTM and OTM calls priced under the price threshold of €0.20. The last two plots refer to the DOTM and OTM calls that are affected by the second stage of the PBTS.

[8] The results are similar for the ITM contracts.

insert Figure 3 around here

Before the tick size changes, the mean trade size was substantially lower than the average quoted depth which suggests that there was plenty of liquidity at the best bid and ask to accommodate larger trades. This finding holds for both price groups and across moneyness levels. However, after the implementation of the new tick size, depth at the best quotes decreased significantly whereas the average trade size remained unchanged. While the market is still able to accommodate the average trades, it becomes clear that trading at the best bid and ask is no longer possible for the larger trades. When the Mean + SD or the Mean + 2SD lines lie above the Quoted Depth line, trades of that magnitude would have to go further down in the order book, implying an overall decrease for the larger trades. It then becomes clear that the ability of the market to absorb larger trades has diminished after the change in the tick size. However, as 60% of trades are conducted by retail traders, we expect that this decrease in liquidity has no effect for the vast majority of traders in the market.

insert Table 2 around here

Table 2 investigates the components of the effective half spread in order to decompose the reduction in spreads to price impact costs and the realized spread. As hypothesized, both price impact and realized spreads fell after the implementation of the PBTS, however this drop is not uniformly significant. In the 1st stage of PBTS, the reduction in price impact is approximately 53% for the DOTM contracts and 63% for the OTM contracts. The drop in realized spreads is relatively higher for the same group of contracts, which implies that the reduction in trade costs documented in Table 1 is driven more by the drop in real costs in that market. As a matter of fact, the large drop in realized spreads for the DOTM and OTM contracts potentially indicates a drop in market making revenues as market makers are obliged to offer liquidity at the deep end of the options market. At the 2nd stage of PBTS, the drop in realized spreads is relatively smaller than the drop in price impact, implying that the increase in trade liquidity spreads is due to a decrease in price impact rather than a decrease in real costs.

Table 3 documents the effect of PBTS on trading activity variables. We anticipate that following the tick size changes, contracts under the price threshold will exhibit an increase in transaction frequency and traded volume.

insert Table 3 around here

As hypothesized, the overall trading volume has significantly increased following the implementation of the 1st stage of PBTS. The increase in volume is 50% (132%) for DOTM calls (puts), 220% (277%) for OTM calls (puts) and 128% (100%) for ITM calls (puts). At the second stage of PBTS, DOTM calls and puts have recorded a greater increase in trading volume than the equivalent DOTM contracts at the first stage of PBTS, and the reverse is true for the OTM contracts.

Also, on average, trading activity for DOTM puts has increased more than trading activity for DOTM calls. The increase in the DOTM options implies that investors take more risk as options become relatively cheaper. The increase in the DOTM puts also coincides with the fact that the market has been declining during the sample period (June 2, 2009 to October 30, 2009), hence an increase in the speculative activity for the long DOTM put investors. For the short DOTM put investors, while this may seem initially as a risky strategy, the short put risk is lower for the lower priced contracts.

Consistent with Hypothesis 5, transaction frequency also increased after the change in the tick size. At stage 1, the average number of trades per day increased by 18% for DOTM calls and 125% for DOTM puts, a finding that reflects the respective liquidity increase in DOTM calls and puts. Clearly, the OTM contracts benefited more in terms of the overall increase in trading activity as the number of trades increased by 172% for calls and 217% for puts. As the price level increased from €0.20 to €0.50, trades for the DOTM calls (puts) increased by 40% (48%). This finding implies that while for DOTM calls, the increase in trades is aligned with the increase in trading volume, for DOTM puts traded volume has increased more than transaction frequency, reflecting an overall increase in the average trade size. ITM calls have not recorded an increase in transaction frequency.

We also hypothesize that spreads will be reduced more for assets that are more heavily traded as it is more likely that the large tick size on these costs acts as a binding constraint for a reduction in spreads. In Table 4 we show evidence in favour of this hypothesis. We classify tickers according to their transaction frequency in subsamples 1 and 3. We then assign subsamples 2 and 4 to quartiles according to their trade frequency and estimate effective half spreads.

insert Table 4 around here

For the 1st stage of PBTS, Table 4 shows that tickers with the fewest number of trades are those that exhibit the smaller decrease in spreads. For the DOTM and OTM calls and puts, spreads narrow by more where the number of trades is greater. For ITM contracts, the reduction in effective spreads is at maximum levels in the medium category. For the second stage of PBTS, the decrease in the minimum tick size had no effect on the liquidity of the low-frequency options. For the tickers with medium and high trade frequency we observe a reduction in spreads that increases as transaction frequency increases, confirming Hypothesis 6.

Hypothesis 7 predicts that the effect of the PBTS in trade and quote liquidity will become less pronounced as moneyness increases, however Table 1 shows some primary evidence against this hypothesis. In particular, across all four liquidity measures liquidity appears to increase more as moneyness increases. However, as we will show later, this initial result is not supported when we control for other changes in the DiD regressions.

We also hypothesize that quote liquidity for the OTM options written on more volatile underlying assets will increase by more compared to equally OTM options written on less volatile underlying assets, due to an increased interest on the former contracts (Hypothesis 8). The opposite effect is expected for the ITM contracts, as volatility will increase the probability of these options moving away from being ITM at expiration. Table 5 shows evidence in support of this hypothesis. For each stage, we use the period before the implementation of the tick size changes to classify tickers based on the underlying's volatility. We then split the sample to low, medium and high volatility tickers and estimate the log quote slope before and after the tick size changes. As hypothesized, for the OTM and DOTM contracts and across both subsamples, quote liquidity increases more for the higher volatility contracts. This finding is consistent with the findings in Table 4. Also in line with the intuition behind Hypothesis 8, for the ITM contracts, quote liquidity increases less as the underlying volatility increases. Interpreting the findings of Table 5 from the perspective of trading costs, the tick size constrains the speculative activities of investors in OTM contracts which have higher underlying asset volatility. The contracts that are more likely to increase in moneyness benefit more from the decreased tick size.

insert Table 5 around here

Contracts that are affected by the changes in the tick size are also expected to exhibit lower volatility if liquidity has overall increased. In Table 3, volatility refers to the standard deviation of absolute returns. For calls, Hypothesis 9 is confirmed. For contracts trading under €0.20, volatility decreased and the decrease is larger for greater moneyness levels. The same finding is reported for puts. For the higher priced contracts, volatility also decreased however the decrease in volatility is relatively constant across moneyness levels.

Regarding the third component of liquidity, execution speed, an important feature of the smaller tick size is that quote revisions may increase, potentially hurting the larger investors and in general constraining traders from posting quotes on the order book. Inevitably, the above would have a negative effect on the depth of the order book. Figure 3 presents the percentage of quote improvements before and after the implementation of PBTS. The procedure is as follows. The dataset is not sampled every five minutes, but instead we use the entire time series at the best bid and ask. For each sub-ticker, we classify a new best bid or best ask as a price improvement when the new ask is smaller than the previous ask or the new bid is greater than the old bid.[9] We follow this procedure separately for calls and puts and

[9] The procedure is conducted in tick time and not in clock time as there are several new quotes per second.

across moneyness levels. We subsequently calculate the percentage of quote improvements per subticker, per day. The results are presented in Figure 4 and also in Table 6.

insert Figure 4 around here

Figure 4 plots the percentage of price improvement for the periods before and after the implementation of the two stages of PBTS. For the DOTM contracts, price improvement is relatively similar for both price levels. The tick size reduction had a clear and substantial effect on the percentage of price improvement for the best bid and ask prices. This finding is confirmed for all moneyness contracts, however the jump in the percentage of price improvement becomes less visible as moneyness increases. We quantify these results in Table 6.

For contracts priced below €0.20, quote improvements increased by 273% (263%) for calls (puts) for the DOTM contracts. That figure is reduced as moneyness increases, hence for the ITM contracts the increase in price improvements is on average 48% for calls and 2.5% for puts. For the second price group (€0.20 - €0.50), similar figures for the percentage of price improvement are reported for the DOTM contracts, however we also show that price improvements remain over 100% across moneyness levels for the whole subsample. This finding is an outcome of the price level effect, as traders have more opportunities to step ahead of higher priced contracts. Overall, our findings show strong support for Hypothesis 10 that the decrease in tick size has potentially led to a deterioration in the order book, as it allows traders to take advantage of the price priority rule and potentially step ahead of larger trades.

insert Table 6 around here

In this final part of the analysis, we use the DiD regressions to quantity the differences in liquidity for tickers affected by the PBTS and also controlling for the changes in liquidity for contracts that are not affected by the PBTS. We also control for the price level, volatility and trading volume for the options market. In these regressions, we use the absolute value of 5-minute intraday returns as a high frequency measure of volatility. For the underlying market, we include the natural logarithm of the market capitalization of the underlying asset, underlying volatility and the closing percentage bid-ask spread. The main variables of interest are Treatment, that shows the level of liquidity of options that are affected by the PBTS rule before the implementation of the PBTS rule, and Treat*Post that shows the change in the liquidity of options priced below the price threshold after the implementation of the PBTS rule.

The results for quoted spread and depth are presented in Table 7. Due to space considerations, we only present the results for calls. The results for puts are similar and available upon request.

insert Table 7 around here

For both price groups, as also confirmed in Table 1, quoted spreads generally narrowed following the tick size reduction. However, in contrast to Table 1, when controlling for the price level, volatility and volume, quoted spreads generally decreased more for lower moneyness levels. This result generally confirms Hypothesis 7 that spreads for the OTM options reduced more than spreads for the ITM options. As anticipated, liquidity is positively related to price level and volatility. Also, the coefficient for volume is negative and highly significant for five out of six regressions. Quoted spreads are smaller for larger firms and increase as the underlying spread increases. The underlying asset volatility has a negative effect on the lower-priced options but no significance is found for the higher-priced contracts.

Table 7 also presents the DiD regression results for the quoted depth. The treat*post variable indicates that depth decreases more as moneyness increases. The findings suggest that, while quoted spread liquidity generally increased more for the DOTM contracts, quoted depth liquidity deteriorated more for contracts that are further in-the-money. This implies that following the tick size changes, liquidity generally increased for the out-of-the-money contracts but decreased for the in-the-money contracts, or at least that the contracts that are further out-of-the-money have benefited more from the decrease in the tick size.

insert Table 8 around here

We present the DiD regression results for the quote and trade liquidity measures in Table 8. Effective half spreads are generally smaller than quoted spreads, a finding that holds across all price groups. Also, the change in trade liquidity is smaller for the effective half spreads than the quoted spreads. The average quoted spread change is 31% for the DOTM contracts priced below €0.20 but 24% for the effective half spread. A similar relationship holds for the 2nd stage of PBTS. Also, the Post variable remains insignificant for the second stage of the

PBTS, suggesting that spreads for the control group have remained constant across the two subperiods. Spreads decrease for higher moneyness levels, a finding that further confirms Hypothesis 7. For the quote liquidity measure, the Treat*Post variable is generally negative and highly significant, implying an increase in quote liquidity after the introduction of PBTS. The findings of Table 8 clearly indicate that PBTS had an overall positive effect on trade and quote liquidity.

6. CONCLUSIONS

On June 2, 2009 NYSE LIFFE introduced the PBTS rule on all single stock options trading at NYSE LIFFE Amsterdam, which allowed equity options trading at a premium of €0.20 or lower to be quoted at a tick size of €0.01, whereas options trading at prices higher than the threshold continued to be quoted at a minimum tick of €0.05. On April 1, 2010, NYSE LIFFE further increased the price threshold from €0.20 to €0.50. This paper presents evidence of the effect of the implementation of the PBTS on the liquidity of individual equity options. In this respect, this study is uniquely positioned in the options context where moneyness is a clear additional factor in the implementation of the tick size changes.

Empirically, in equity and futures markets, several studies have shown that spreads generally decrease following the reduction in tick size. However, market depth deteriorates as a smaller tick size makes front running more profitable for smaller investors and increases order transparency for large traders. The latter implies an overall increase in liquidity for small trades and an overall decrease for institutional traders. In general, the issue is far from being resolved in favour of the smaller tick size and following criticisms from the industry, in June 2013, the Securities and Exchange Commission has been reported to draft a pilot program that would increase the tick size for 100 of the smaller or less liquid US stocks.

Our findings suggest that, while quoted spread liquidity generally increased more for the deep-out-of-the-money options, quoted depth liquidity deteriorated more for contracts that are further ITM, implying an increase in liquidity for the out-of-the-money contracts but a decrease for the in-the-money contracts. Effective spreads have decreased more than quoted spreads for contracts with low moneyness, but the significance disappears as moneyness increases. For the lower-priced contracts, the drop in effective spreads is due to an overall decrease in real costs net of the price impact of trades, but the decrease in real costs disappears when the price threshold increased to €0.50.

Importantly, we show that the ability of the market to absorb larger trades has diminished after the change in the tick size, which is however expected to have no effect for the vast majority of traders in the market as Amsterdam is dominated by retail investors. We document a substantial increase in quote revisions that implies that the decrease in tick size has potentially led to a worsening of the order book, as it allows traders to take advantage of the price priority rule and step ahead of larger trades. Finally, we document an increase in the speculative trading activity for the deep-out-of-the-money contracts which has also resulted to a substantial increase in option volatility.

Our findings have important implications for optimal contract design in the equity options market. The goal of attracting liquidity has been achieved with two immediate implications: economic rents have been transferred from market makers to individual investors and the increase in liquidity has been realized at the expense of a thinner market for larger investors. The price/time priority rule may not work in circumstances when a large trade enters the market and, in such occasions, market makers should be allowed to increase their economic rents for facilitating abnormal trade sizes in ways similar to an upstairs market. A second possible scenario would be for the exchange to introduce a pro-rata algorithm that will circumvent the problem with the price priority rule when the tick size is too small.

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Table 1
Measures of quoted and traded liquidity

			Call			Put		
			DOTM	OTM	ITM	DOTM	OTM	ITM
Quoted Spread	1st Stage	Before	61.60	51.44	48.30	59.64	49.69	46.08
		After	40.60	26.28	21.36	41.64	23.73	19.42
		% diff	-34.09***	-48.91***	-55.77***	-30.18***	-52.24***	-57.85***
	2nd Stage	Before	19.38	18.28	16.53	19.07	18.15	16.43
		After	13.89	11.23	8.77	12.27	10.34	8.67
		% diff	-28.32***	-38.56***	-46.94***	-35.65***	-43.03***	-47.23***
Quoted depth	1st Stage	Before	895.81	1131.34	1144.93	995.16	1161.11	1401.83
		After	378.81	378.37	413.04	383.21	385.44	411.90
		% diff	-57.71***	-66.55***	-63.92***	-61.49***	-66.8***	-70.61***
	2nd Stage	Before	861.63	1095.07	1352.92	908.39	1156.35	1371.55
		After	293.22	347.31	412.97	364.89	392.07	426.51
		% diff	-65.96***	-68.28***	-69.47***	-59.83***	-66.09***	-68.90***
Log Quote Slope	1st Stage	Before	0.056	0.043	0.042	0.053	0.041	0.039
		After	0.044	0.028	0.024	0.046	0.025	0.022
		% diff	-21.42***	-34.88***	-42.85***	-13.2***	-39.02***	-43.58***
	2nd Stage	Before	0.017	0.016	0.013	0.017	0.015	0.013
		After	0.015	0.013	0.009	0.013	0.011	0.009
		% diff	-11.76***	-18.75***	-30.76***	-23.52***	-26.66***	-30.76***
Effective Half Spread	1st Stage	Before	42.08	35.75	32.97	39.89	34.25	30.33
		After	21.73	14.76	13.68	22.63	14.86	12.75
		% diff	-48.36***	-58.71***	-58.50***	-43.26***	-56.61***	-57.96***
	2nd Stage	Before	16.89	15.85	13.31	16.70	15.57	12.89
		After	9.54	7.52	5.26	8.72	7.32	5.00
		% diff	-43.51***	-52.55***	-60.48***	-47.78***	-52.98***	-61.21***

% Quoted spread is estimated as 100*($Ask_{5\text{-}min}$ – $Bid_{5\text{-}min}$)/$Midquote_{5\text{-}min}$, where midquote refers to the average of bid and ask price. Quoted depth refers to the average number of contracts at the ask and bid price, estimated in 5-minute intervals. Log Quote Slope is estimated as ($Ask_{5\text{-}min}$ – $Bid_{5\text{-}min}$)/(log($Volume_{ask,\ 5\text{-}min}$) + log($Volume_{bid,\ 5\text{-}min}$)), % Effective spread is estimated as 200*D*($Price_t$ – $Midquote_t$)/$Midquote_t$, where D refers to a trade indicator dummy that takes the value of -1 is the trade is classified as a sell and +1 if it is classified as a buy. The first stage refers to the period around the first implementation of PBTS (June 02, 2009) and the second stage refers to the dates around the second implementation of PBTS (April 1, 2010). Before and after refer to 150-day estimation windows. For calls, we define DOTM contracts with moneyness smaller than 0.9, OTM contracts with moneyness equal to 0.9 but smaller than 1.00 and ITM contracts with moneyness between or equal to 1.00 and 1.10. The opposite classification is used for puts. *, **, *** denote significance at 10%, 5% and 1% levels, respectively.

Table 2
Realized spread and price impact

			Call			Put		
			DOTM	OTM	ITM	DOTM	OTM	ITM
Price Impact	1st Stage	Before	24.84	24.65	28.81	23.97	23.04	22.59
		After	10.51	9.11	7.10	10.15	8.47	9.08
		% diff	-57.68***	-63.04***	-75.35	-57.65***	-63.23***	-59.80
	2nd Stage	Before	10.88	11.15	9.31	11.24	11.34	9.45
		After	5.61	5.27	3.68	5.24	5.29	3.35
		% diff	-48.43***	-52.73***	-60.47***	-53.38***	-53.35***	-64.55***
Realized Spread	1st Stage	Before	16.18	13.40	7.06	15.04	12.45	11.71
		After	6.42	3.61	2.96	6.88	3.69	1.01
		% diff	-60.32***	-73.05***	-58.07**	-54.25***	-70.36***	-91.37
	2nd Stage	Before	5.41	4.12	3.72	4.78	3.89	3.38
		After	2.82	1.67	0.96	2.38	1.28	1.10
		% diff	-47.87***	-59.46	-74.19	-50.20***	-67.09**	-67.45

% Realized spread is estimated as $200*D*(Price_t – Midquote_{t+1})/Midquote_t$, where D refers to a trade indicator dummy that takes the value of -1 is the trade is classified as a sell and +1 if it is classified as a buy. % Price impact is estimated as $200*D*(Midquote_{t+1} – Midquote_t)/Midquote_t$. The first stage refers to the period around the first implementation of PBTS (June 02, 2009) and the second stage refers to the dates around the second implementation of PBTS (April 1, 2010). Before and after refer to 150-day estimation windows. For calls, we define DOTM contracts with moneyness smaller than 0.9, OTM contracts with moneyness equal to 0.9 but smaller than 1.00 and ITM contracts with moneyness between or equal to 1.00 and 1.10. The opposite classification is used for puts. *, **, *** denote significance at 10%, 5% and 1% levels, respectively.

Table 3
Trading activity and volatility

			Call			Put		
			DOTM	OTM	ITM	DOTM	OTM	ITM
Traded volume	1st Stage	Before	11365.52	3780.21	337.50	6063.52	1738.92	200.93
		After	17090.36	12100.3	770.85	14121.94	6549.01	402.69
		% diff	50.37***	220.09***	128.4***	132.9***	276.61***	100.41***
	2nd Stage	Before	5716.99	15974.12	5638.36	5200.63	9628.09	2954.12
		After	10318.66	24612.85	6387.93	12627.98	17212.51	4041.42
		% diff	80.49***	54.07***	13.29	142.81***	78.77***	36.8***
Trades	1st Stage	Before	247.32	80.56	7.97	136.25	42.62	6.57
		After	292.78	219.67	17.24	307.77	135.52	10.46
		% diff	18.38**	172.67***	116.31***	125.88***	217.97***	59.20***
	2nd Stage	Before	164.97	465.75	144.65	142.35	303.47	97.96
		After	231.81	590.84	157.80	211.37	366.07	108.40
		% diff	40.51***	26.85***	9.09	48.48***	20.62***	10.65***
Volatility	1st Stage	Before	5.16	5.92	7.06	4.43	5.31	5.75
		After	4.57	4.42	4.20	4.35	4.14	4.15
		% diff	-11.43***	-25.33***	-40.50***	-1.80**	-22.03***	-27.82*
	2nd Stage	Before	3.28	3.62	3.40	2.96	3.50	3.24
		After	2.10	2.48	2.18	1.93	2.29	2.07
		% diff	-35.97***	-31.49***	-35.88***	-34.79***	-34.57***	-36.11***

Traded volume refers to the average volume per day, Trades refer to the total number of transactions per day and Volatility is estimated as the standard deviation of the absolute value of intraday 5-minute returns. The first stage refers to the period around the first implementation of PBTS (June 02, 2009) and the second stage refers to the dates around the second implementation of PBTS (April 1, 2010). Before and after refer to 150-day estimation windows. For calls, we define DOTM contracts with moneyness smaller than 0.9, OTM contracts with moneyness equal to 0.9 but smaller than 1.00 and ITM contracts with moneyness between or equal to 1.00 and 1.10. The opposite classification is used for puts. *, **, *** denote significance at 10%, 5% and 1% levels, respectively.

Table 4
Traded liquidity by transaction frequency

			Call			Put		
			DOTM	OTM	ITM	DOTM	OTM	ITM
Low	1st Stage	Before	43.39	33.82	32.85	40.59	38.95	37.14
		After	26.10	24.38	19.31	33.44	22.50	19.06
		% diff	-39.84***	-27.91***	-41.21***	-17.61**	-42.23***	-48.68***
	2nd Stage	Before	20.36	20.39	17.96	20.31	20.62	15.34
		After	18.31	14.62	9.67	17.67	16.01	8.340
		% diff	-10.06	-28.29	-46.15	-12.99*	-22.35	-45.63
Medium	1st Stage	Before	42.67	38.04	37.08	38.34	35.63	31.97
		After	25.60	17.95	11.20	24.02	16.60	10.48
		% diff	-40.00***	-52.81***	-69.79***	-37.35***	-53.41***	-67.21***
	2nd Stage	Before	17.42	17.18	13.92	17.36	16.47	13.23
		After	11.64	9.52	7.49	10.80	8.87	6.89
		% diff	-33.18***	-44.58***	-46.19	-37.78***	-46.14**	-47.92
High	1st Stage	Before	41.85	35.38	31.10	40.19	33.74	28.76
		After	20.26	13.52	12.90	21.09	14.03	13.46
		% diff	-51.58***	-61.78***	-58.52***	-47.52***	-58.41***	-53.19***
	2nd Stage	Before	16.62	15.38	13.18	16.27	15.18	12.8
		After	8.33	6.71	4.87	7.45	6.63	4.70
		% diff	-49.87***	-56.37***	-63.05***	-54.21***	-56.32***	-63.28**

Traded liquidity refers to effective spread, estimated as $200*D*(Price_t - Midquote_t)/Midquote_t$, where D refers to a trade indicator dummy that takes the value of -1 is the trade is classified as a sell and +1 if it is classified as a buy. Low, medium and high refer to daily transaction frequency. Low refers to the 1st quartile and High to the 4th quirtile. Medium refers to the 2nd and 3rd quirtile. The first stage refers to the period around the first implementation of PBTS (June 02, 2009) and the second stage refers to the dates around the second implementation of PBTS (April 1, 2010). Before and after refer to 150-day estimation windows. For calls, we define DOTM contracts with moneyness smaller than 0.9, OTM contracts with moneyness equal to 0.9 but smaller than 1.00 and ITM contracts with moneyness between or equal to 1.00 and 1.10. The opposite classification is used for puts. *, **, *** denote significance at 10%, 5% and 1% levels, respectively.

Table 5
Quoted liquidity by underlying volatility

			Call			Put		
			DOTM	OTM	ITM	DOTM	OTM	ITM
Low	1st Stage	Before	0.054	0.041	0.039	0.049	0.039	0.04
		After	0.046	0.026	0.016	0.048	0.023	0.015
		% diff	-14.81*	-36.58***	-58.97***	-2.04	-41.02***	-62.5***
	2nd Stage	Before	0.019	0.015	0.012	0.017	0.014	0.012
		After	0.017	0.011	0.008	0.013	0.01	0.008
		% diff	-10.52*	-26.66***	-33.33	-23.52***	-28.57***	-33.33
Medium	1st Stage	Before	0.062	0.049	0.037	0.062	0.046	0.034
		After	0.048	0.035	0.016	0.052	0.031	0.017
		% diff	-22.58***	-28.57***	-56.75***	-16.12***	-32.6***	-50***
	2nd Stage	Before	0.021	0.019	0.018	0.02	0.019	0.018
		After	0.019	0.018	0.016	0.017	0.016	0.017
		% diff	-9.52	-5.26***	-11.11	-15***	-15.78***	-5.55
High	1st Stage	Before	0.054	0.045	0.048	0.05	0.043	0.042
		After	0.04	0.028	0.036	0.04	0.025	0.028
		% diff	-25.92***	-37.77***	-25***	-20***	-41.86***	-33.33***
	2nd Stage	Before	0.015	0.015	0.014	0.015	0.014	0.013
		After	0.013	0.011	0.009	0.01	0.01	0.009
		% diff	-13.33	-26.66***	-35.71***	-33.33***	-28.57***	-30.76***

Quoted liquidity refers to log quote slope estimated as $(Ask_{5\text{-min}} - Bid_{5\text{-min}})/(\log(Volume_{ask,\,5\text{-min}}) + \log(Volume_{bid,\,5\text{-min}}))$. We use the range estimator as a measure of the underlying market volatility. We use the period before the implementation of the tick size changes to classify tickers based on liquidity. The first stage refers to the period around the first implementation of PBTS (June 02, 2009) and the second stage refers to the dates around the second implementation of PBTS (April 1, 2010). Before and after refer to 150-day estimation windows. For calls, we define DOTM contracts with moneyness smaller than 0.9, OTM contracts with moneyness equal to 0.9 but smaller than 1.00 and ITM contracts with moneyness between or equal to 1.00 and 1.10. The opposite classification is used for puts. *, **, *** denote significance at 10%, 5% and 1% levels, respectively.

Table 6
% Price improvement

		Call			Put		
		DOTM	OTM	ITM	DOTM	OTM	ITM
1st Stage	Before	4.20	4.53	11.55	4.39	4.45	18.23
	After	15.7	15.17	17.70	15.77	16.16	17.67
	% diff	273.80***	234.87***	53.24*	259.22***	263.14***	-3.07***
2nd Stage	Before	5.42	6.07	5.80	5.43	6.53	6.16
	After	17.87	16.72	15.34	17.43	16.55	15.17
	% diff	229.70***	175.45***	164.48***	220.99***	153.44***	146.26***

For the calculation of % Price improvement we use the entire time series at the best bid and ask and for each subticker, we classify a new best bid or best ask as a price improvement when the new ask is smaller than the previous ask or the new bid is greater than the old bid.We follow this procedure separately for calls and puts and across moneyness levels. We subsequently calculate the percentage of quote improvements per subticker, per day.The first stage refers to the period around the first implementation of PBTS (June 02, 2009) and the second stage refers to the dates around the second implementation of PBTS (April 1, 2010). Before and after refer to 150-day estimation windows. For calls, we define DOTM contracts with moneyness smaller than 0.9, OTM contracts with moneyness equal to 0.9 but smaller than 1.00 and ITM contracts with moneyness between or equal to 1.00 and 1.10. The opposite classification is used for puts. *, **, *** denote significance at 10%, 5% and 1% levels, respectively.

Table 7
DID Quoted Spread and Quoted Depth

	Spread						Depth					
	1st stage			2nd stage			1st stage			2nd stage		
	DOTM	OTM	ITM	DOTM	OTM	ITM	DOTM	OTM	ITM	DOTM	OTM	ITM
Constant	17.91***	13.08***	7.06***	13.65***	13.97***	10.00***	-1671.26***	-2667.05***	-3345.41***	-1635.56***	-2546.86***	-3381.62***
	(23.46)	(35.82)	(15.91)	(23.22)	(43.27)	(34.44)	(-16.89)	(-36.24)	(-41.82)	(-23.10)	(-38.54)	(-39.35)
Treatment	27.77***	23.69***	12.42***	3.65***	3.64***	3.10***	201.20***	281.39***	-539.19***	238.37***	233.34***	108.97***
	(104.73)	(72.25)	(10.70)	(36.16)	(60.76)	(44.34)	(16.19)	(14.70)	(-5.96)	(15.67)	(21.04)	(5.61)
Post	-1.33***	-0.56***	-0.79***	1.78***	0.89***	0.22***	19.64	-8.00	69.50***	-109.66***	-75.40***	161.22***
	(-11.38)	(-8.11)	(-11.42)	(20.94)	(19.38)	(4.28)	(0.64)	(-0.34)	(3.01)	(-4.54)	(-3.46)	(5.01)
Treat*Post	-30.95***	-28.04***	-24.91***	-10.04***	-10.03***	-9.08***	-553.83***	-878.09***	-1006.17***	-613.57***	-751.72***	-1004.59***
	(-120.45)	(-96.68)	(-20.79)	(-64.57)	(-114.74)	(-100.78)	(-23.00)	(-32.63)	(-10.99)	(-27.48)	(-39.93)	(-29.48)
Volatility	0.38***	0.22***	0.18***	0.47***	0.31***	0.33***	-32.18***	-25.08***	-20.69***	-24.6***	-35.15***	-46.21***
	(26.36)	(29.99)	(29.58)	(23.42)	(46.00)	(49.89)	(-23.23)	(-27.12)	(-17.29)	(-22.54)	(-33.22)	(-24.88)
1/Pr	2.82***	2.48***	4.22***	4.13***	3.75***	3.16***	1.24***	3.15***	226.28***	74.63***	94.37***	241.21***
	(97.82)	(65.24)	(22.37)	(95.79)	(124.41)	(70.13)	(2.86)	(3.95)	(15.89)	(20.64)	(24.54)	(25.14)
Volume	0.90***	1.92***	1.89***	-0.98***	0.16***	0.96***	.	.	.	.	.	.
	(8.79)	(40.27)	(41.63)	(-7.45)	(3.60)	(22.04)	.	.	.	.	.	.
Under MV	-1.71***	-1.99***	-1.69***	-0.47***	-1.21***	-1.33***	248.16***	380.91***	441.76***	229.32***	338.65***	456.81***
	(-20.63)	(-46.14)	(-49.78)	(-5.31)	(-30.42)	(-36.97)	(26.21)	(55.62)	(60.63)	(31.71)	(52.04)	(54.55)
PBAS	1.92***	1.65***	1.20***	4.15***	4.02***	3.90***	-13.40***	13.43***	18.65***	22.62***	206.32***	-60.84***
	(2.70)	(4.59)	(4.36)	(4.48)	(8.11)	(9.63)	(-0.14)	(0.19)	(0.29)	(0.26)	(2.90)	(-0.73)
Under Volt	-0.23***	-0.23***	-0.16***	0.07	0.01	< 0.01	64.68***	78.16***	73.99***	57.56***	97.85***	85.37***
	(-7.37)	(-13.18)	(-12.07)	(1.63)	(0.61)	(0.05)	(11.30)	(16.15)	(14.71)	(8.15)	(14.16)	(10.26)
R^2	0.74	0.75	0.46	0.36	0.45	0.41	0.27	0.35	0.40	0.37	0.39	0.45

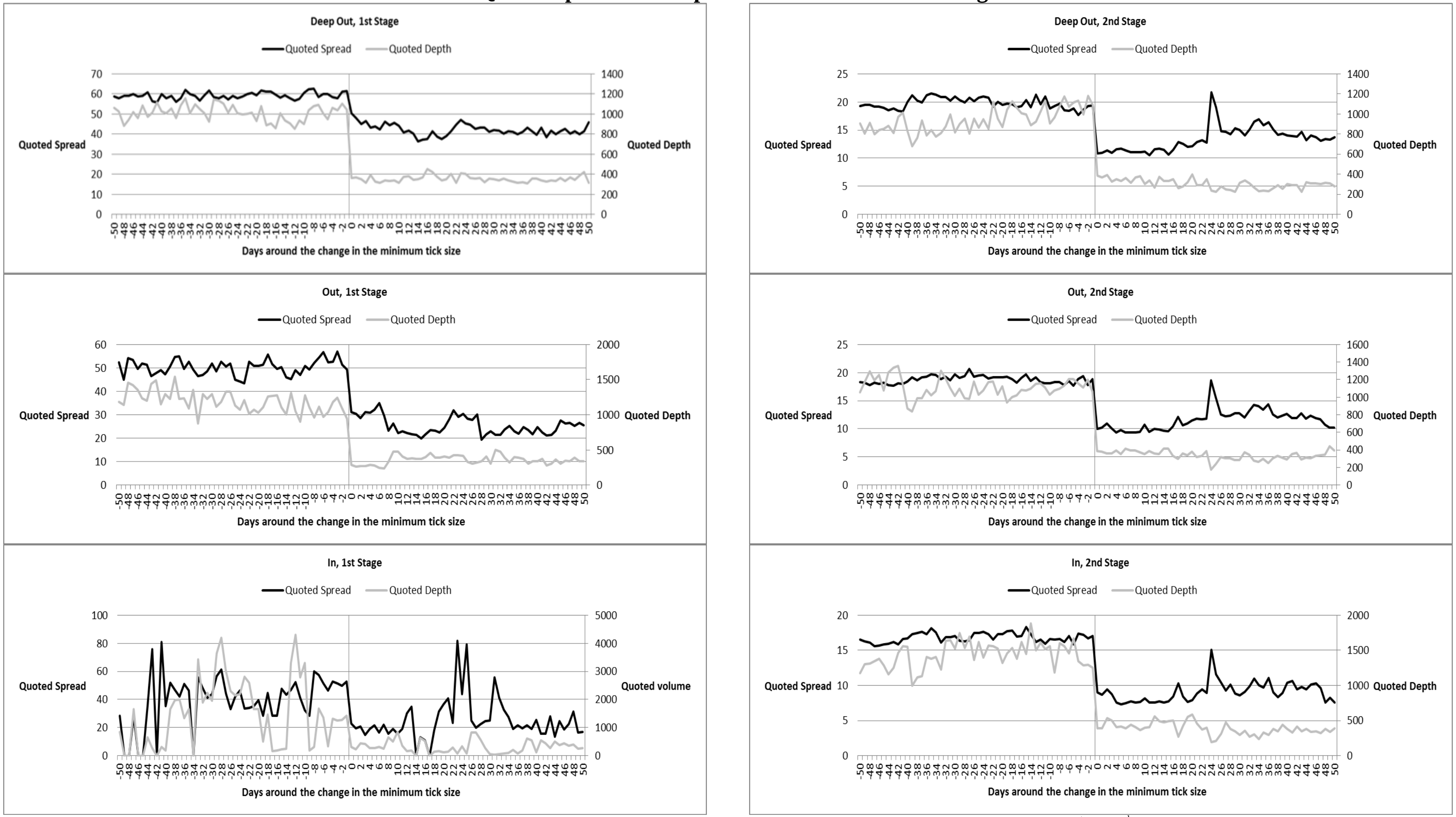
Spread refers to quoted spread and depth refers to quoted depth. Treatment is a dummy variable that takes the value of 1 for options that are affected by the implementation of the PBTS. Post is a dummy variable that takes the value of 1 for the dates after the implementation of the PBTS. Volatility is estimated as the absolute value of intraday 5-minute returns. Pr refers to option price, Volume is the natural logarithm of trading volume per interval, Under MV refers to the natural logarithm of market capitalization of the underlying asset, PBAS refers to the underlying percentage bid-ask spread and Under Volt refers to the underlying volatility estimated used the range estimator. The first stage refers to the period around the first implementation of PBTS (June 02, 2009) and the second stage refers to the dates around the second implementation of PBTS (April 1, 2010). Before and after refer to 150-day estimation windows. For calls, we define DOTM contracts with moneyness smaller than 0.9, OTM contracts with moneyness equal to 0.9 but smaller than 1.00 and ITM contracts with moneyness between or equal to 1.00 and 1.10. The opposite classification is used for puts. *, **, *** denote significance at 10%, 5% and 1% levels, respectively.

Table 8
DID Traded and Quoted Liquidity

	Effective Half Spread						Log Quote Slope					
	1st stage			2nd stage			1st stage			2nd stage		
	DOTM	OTM	ITM	DOTM	OTM	ITM	DOTM	OTM	ITM	DOTM	OTM	ITM
Constant	17.31***	14.90***	5.23***	14.71***	14.09***	5.47***	0.04***	0.02***	0.01***	0.02***	0.02***	0.01***
	(16.94)	(17.47)	(8.85)	(11.12)	(19.94)	(14.83)	(31.27)	(54.59)	(31.10)	(22.64)	(50.88)	(49.92)
Treatment	23.36***	20.35***	10.53***	3.89***	3.75***	2.91***	2.10E-2***	1.60E-2***	9.00E-2***	2.00E-2***	2.00E-2***	2.00E-2***
	(56.63)	(43.81)	(6.39)	(9.39)	(18.48)	(20.08)	(53.26)	(40.81)	(6.76)	(14.43)	(30.09)	(29.49)
Post	-1.32***	-0.60***	-0.01	-0.09	-0.07	0.01	-2.00E-2***	< 0.001***	-1.00E-2***	3.00E-2***	1.00E-2***	< 0.001***
	(-5.17)	(-3.29)	(-0.35)	(-0.25)	(-0.47)	(0.30)	(-8.31)	(-2.96)	(-8.73)	(15.09)	(15.03)	(3.56)
Treat*Post	-23.90***	-22.37***	-17.02***	-8.01***	-8.53***	-8.39***	-2.20E-2***	-2.00E-2***	-1.70E-2***	-5.00E-2***	-6.00E-2***	-6.00E-2***
	(-57.69)	(-45.58)	(-12.40)	(-18.18)	(-40.97)	(-66.45)	(-53.00)	(-57.60)	(-10.63)	(-29.34)	(-56.41)	(-77.59)
Volatility	0.22***	0.16***	-0.01	0.40***	0.35***	0.05***	1.00E-2***	< 0.001***	< 0.001***	1.00E-2***	< 0.001***	0.00E2***
	(4.77)	(4.88)	(-1.39)	(5.80)	(9.28)	(4.39)	(29.12)	(23.73)	(21.67)	(17.02)	(33.65)	(36.31)
1/Pr	1.23***	1.12***	2.69***	2.34***	2.33***	2.40***	3.00E-2***	2.00E-2***	4.00E-2***	4.00E-2***	3.00E-2***	2.00E-2***
	(30.12)	(25.20)	(8.35)	(13.91)	(23.33)	(22.57)	(77.24)	(48.44)	(17.83)	(58.77)	(89.38)	(57.65)
Under MV	-0.76***	-0.65***	-0.22***	-0.77***	-0.87***	-0.24***	-4.00E-2***	-2.00E-2***	-1.00E-2***	-2.00E-2***	-2.00E-2***	-2.00E-2***
	(-7.74)	(-9.18)	(-7.79)	(-6.84)	(-14.58)	(-8.76)	(-31.30)	(-48.83)	(-47.90)	(-23.51)	(-50.51)	(-45.53)
Volume	-0.59***	-0.38***	0.01	-0.46***	-0.14***	0.09***	.	.	.	.	.	.
	(-8.03)	(-7.35)	(0.77)	(-5.60)	(-3.70)	(3.26)	.	.	.	.	.	.
PBAS	0.53	1.38	-0.34	1.55	1.07	0.42	5.00E-2***	3.00E-2***	2.00E-2***	7.00E-2***	6.00E-2***	5.00E-2
	(0.55)	(1.39)	(-0.95)	(0.93)	(1.12)	(1.25)	(3.63)	(5.72)	(5.89)	(4.22)	(8.15)	(10.21)
Under Volt	-0.21***	-0.19***	0.02**	-0.23***	-0.25***	0.02*	-1.00E-2***	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***
	(-6.74)	(-4.90)	(2.46)	(-3.10)	(-5.90)	(1.67)	(-11.11)	(-10.37)	(-9.74)	(-3.44)	(-4.17)	(1.18)
R^2	0.37	0.16	0.36	0.04	0.04	0.39	0.62	0.65	0.46	0.23	0.37	0.42

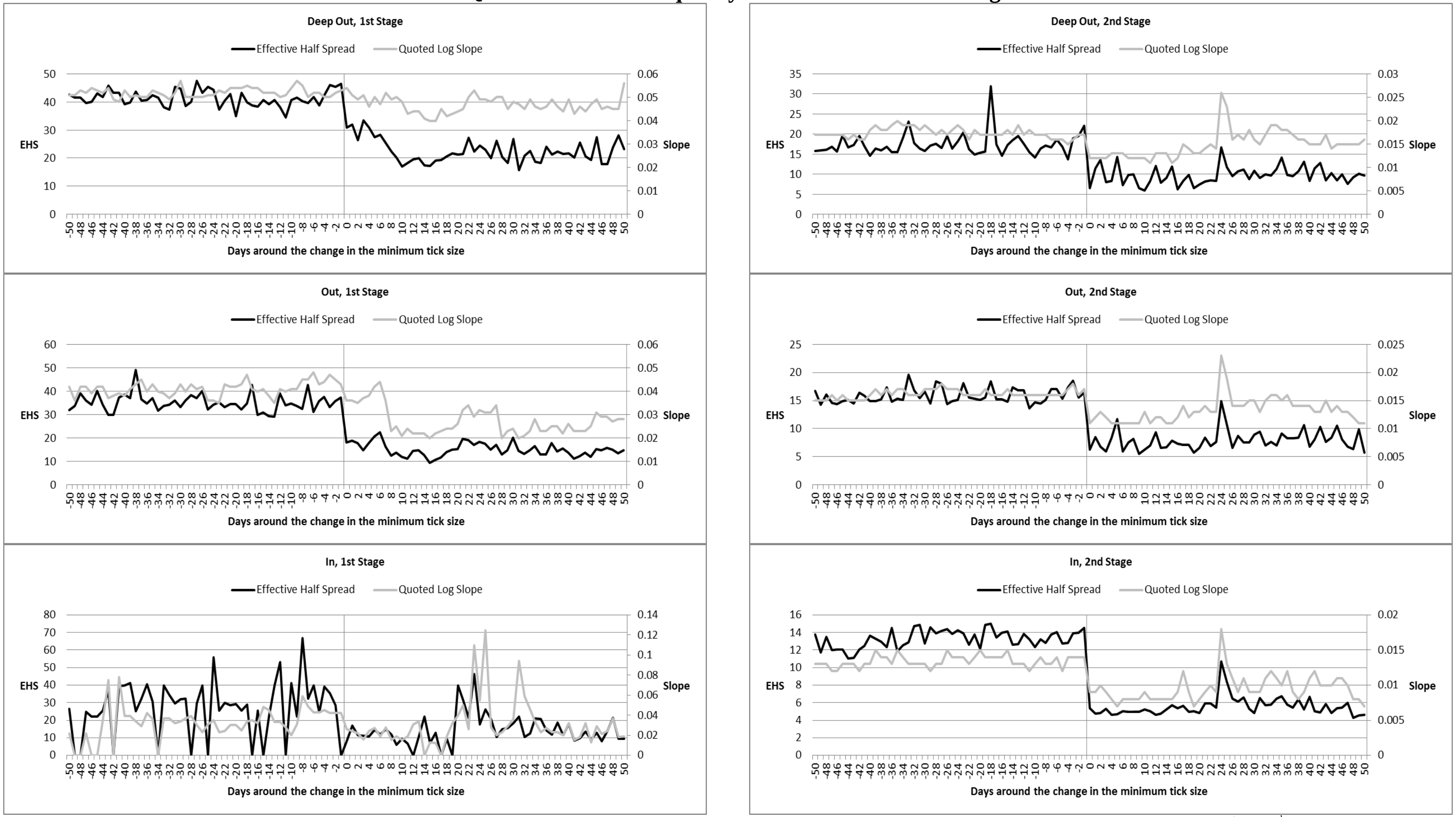
Traded liquidity refers to effective spread, estimated as $200 \cdot D \cdot (Price_t - Midquote_t)/Midquote_t$, where D refers to a trade indicator dummy that takes the value of -1 is the trade is classified as a sell and +1 if it is classified as a buy. Quoted liquidity refers to log quote slope estimated as $(Ask_{5\text{-min}} - Bid_{5\text{-min}})/(\log(Volume_{ask,\ 5\text{-min}}) + \log(Volume_{bid,\ 5\text{-min}}))$. Treatment is a dummy variable that takes the value of 1 for options that are affected by the implementation of the PBTS. Post is a dummy variable that takes the value of 1 for the dates after the implementation of the PBTS. Volatility is estimated as the absolute value of intraday 5-minute returns. Pr refers to option price, Volume is the natural logarithm of trading volume per interval, Under MV refers to the natural logarithm of market capitalization of the underlying asset, PBAS refers to the underlying percentage bid-ask spread and Under Volt refers to the underlying volatility estimated used the range estimator. The first stage refers to the period around the first implementation of PBTS (June 02, 2009) and the second stage refers to the dates around the second implementation of PBTS (April 1, 2010). Before and after refer to 150-day estimation windows. For calls, we DOTM contracts with moneyness smaller than 0.9, OTM contracts with moneyness equal to 0.9 but smaller than 1.00 and ITM contracts with moneyness between or equal to 1.00 and 1.10. The opposite classification is used for puts. *, **, *** denote significance at 10%, 5% and 1% levels, respectively.

Figure 1
Quoted spread and depth around the tick size change



This figure plots the average quoted spread and quoted depth for contracts trading around the implementation of the PBTS. The horizontal axis refers to days to and from the 1st and 2nd stage of PBTS. Due to space considerations, we only present the result for call contracts.

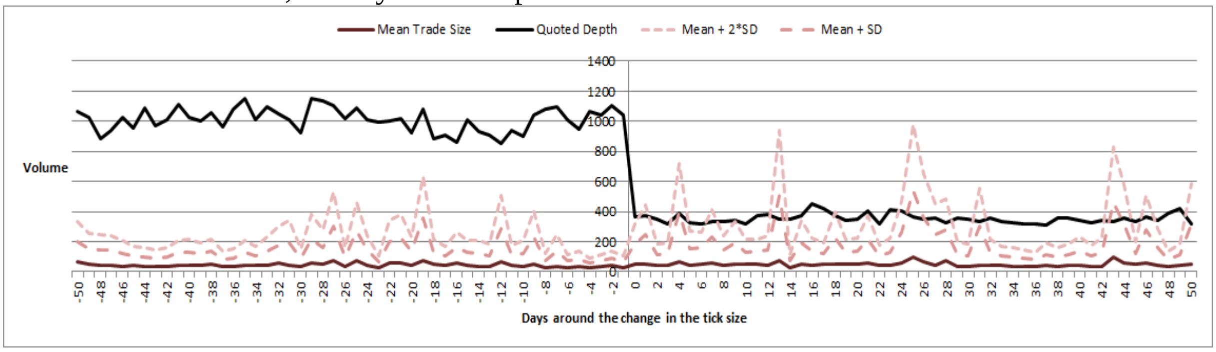
Figure 2
Quoted and traded liquidity around the tick size change



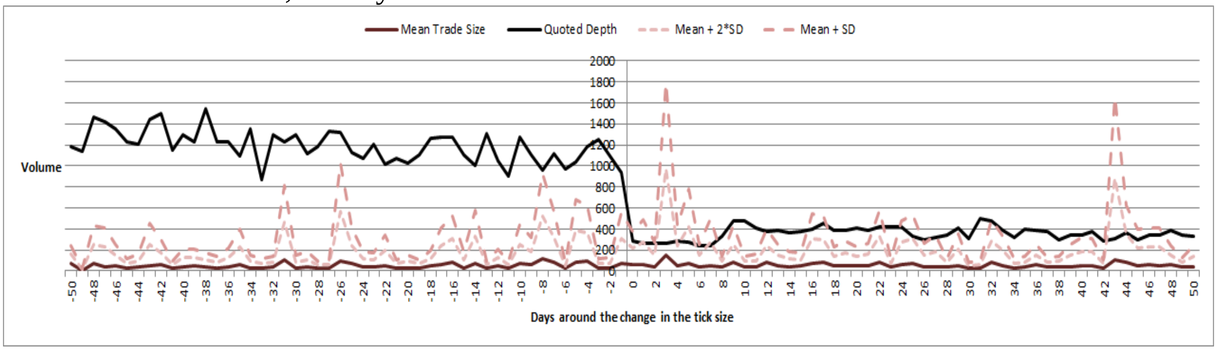
This figure plots the average effective half spread (EHS) and quoted log slope (Slope) for contracts trading around the implementation of the PBTS. The horizontal axis refers to days to and from the 1st and 2nd stage of PBTS. Due to space considerations, we only present the result for call contracts.

Figure 3
Average depth and trade size around the tick size change

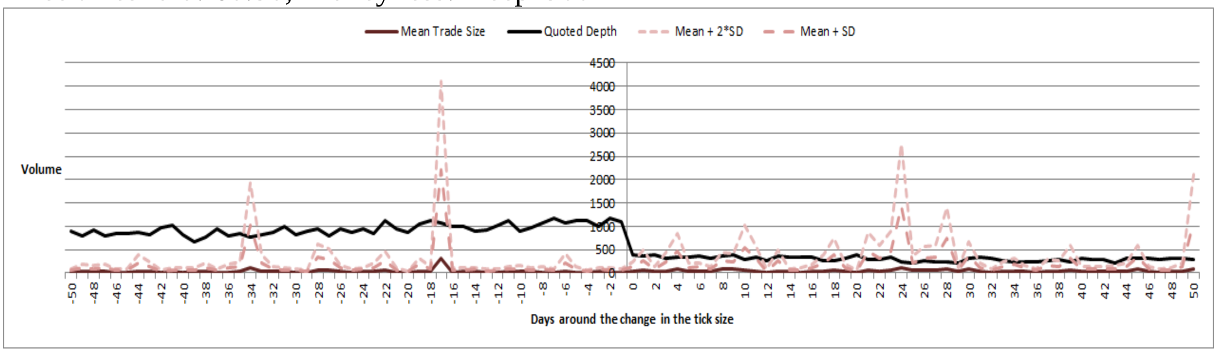
Price threshold: €0.20, Moneyness: Deep Out



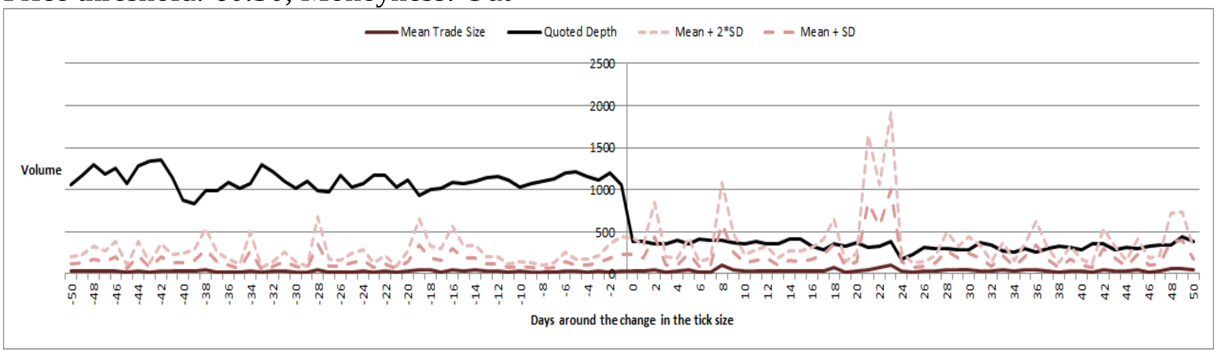
Price threshold: €0.20, Moneyness: Out



Price threshold: €0.50, Moneyness: Deep Out

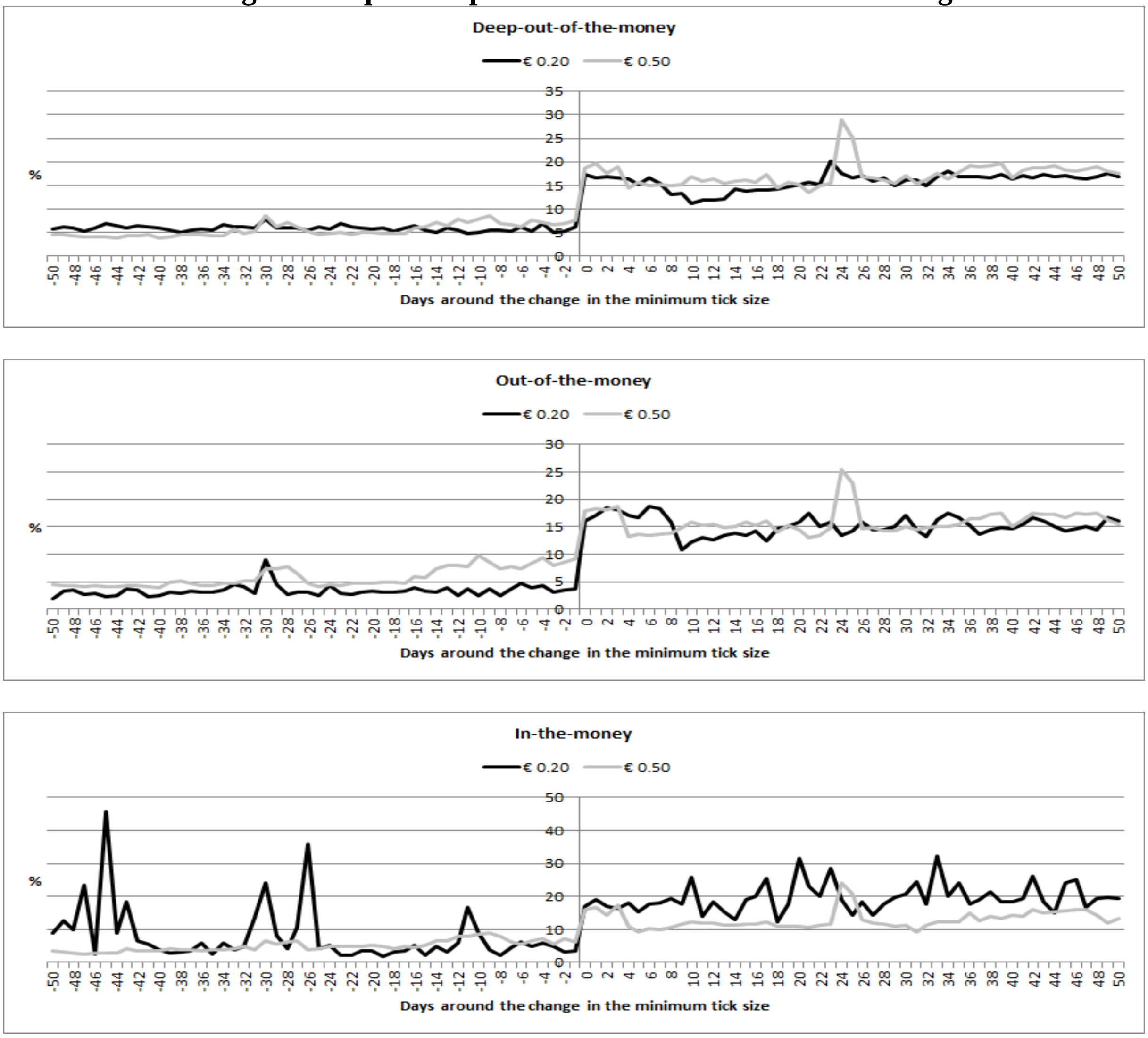


Price threshold: €0.50, Moneyness: Out



This figure plots the average trade size and quoted depth the around the implementation of the PBTS. SD refers to the standard deviation of the mean trade size. For the first (last) two plots, the horizontal axis refers to days to and from to June 2, 2009 (April 1, 2010) (day 0). Due to space considerations, we only present the result for call contracts.

Figure 4
Average mean quote improvement around the tick size changes



This figure plots the percentage of price improvement for the periods before and after the implementation of the two stages of PBTS. , we classify a new best bid or best ask as a price improvement when the new ask is smaller than the previous ask or the new bid is greater than the old bid. The horizontal axis refers to days to and from the 1st and 2nd stage of PBTS.